Report of the RSK Committee on ELECTRIC INSTALLATIONS (EE)

Testing and monitoring programme for oil-paper insulated transformers and dry transformers in German nuclear power plants

1 Introduction

On 28/06/2007, reactor scram occurred at the Krümmel nuclear power plant (KKK), caused by the temporary loss of the auxiliary power supply during a short-circuit in a generator transformer with subsequent fire development (ME 2007/001). After the transformer fire, TÜV Nord and IEH (Department of High Voltage Technology (IEH) of Leibniz Universität Hannover) developed an inspection programme for transformers by order of the Schleswig-Holstein Ministry of Social Affairs, Health, Family, Youth and Senior Citizens (MSGF). Following up the event, the working order of the transformers at KKK was to be demonstrated with the help of this programme, and a concept of necessary in-service inspections (*Wiederkehrenden Prüfungen - WKP*) and monitoring measures for transformers was to be developed, taking the state of the art in science and technology into account.

After the event in 2007, the experts from the nuclear supervisory authority pursued not only the root cause of the transformer fire but also the question of whether such a type of damage could also be prevented in future. They concluded that it was not possible to preclude such damage completely, but that the occurrence frequency of this kind of damage could be reduced through improved monitoring and an improved maintenance and inspection concept. In the root cause analysis of the transformer fire, the main focus was on the question of influences of ageing effects. Moreover, the remaining transformers, which were about the same age as the transformer that burnt down, were examined. Hence the inspection programme contains measures for early damage detection and prevention and is to allow a verification of the good working order of transformers that have aged during operation or have been strained by extraordinary load cases. Furthermore, the inspection programme is to supplement existing maintenance and WKP concepts for transformers in nuclear power plants. Apart from the insights gained from the transformer fire in June 2007, findings from three other events in KKK (response of the Buchholz relay of an emergency power transformer in March 2009 (ME 2009/001), disconnection of a station service transformer by response of a protective device (Buchholz relay) of a tap changer in July 2009, and failure of a generator transformer in July 2009 with turbine trip and reactor scram (ME 2009/003)) were taken into account.

VGB developed its own inspection concept. To do so, the VGB Working Group on "Transformer monitoring" dealt with the monitoring and inspection scope for the determination of the condition of operational generator, station service (> 20 MVA) and offsite system transformers as well as of safety-relevant emergency power transformers in all German nuclear power plants. In this context, the aim was to establish a uniform standard in all German nuclear power plants with regard to the scope and cycles of transformer monitoring in order to ensure comparability of the monitoring and gain generic knowledge. The exchange of experience is steadily continued.

The two inspection and monitoring concepts that were presented are largely congruent.

In the following, the information that the Committee received with respect to the inspection programmes for transformers and the corresponding results of the discussion are presented. Apart from oil-paper-insulated transformers, dry transformers, which are often used as emergency power transformers, are also dealt with.

The discussions among the Committee about the generic safety-related aspects of the above-mentioned events at KKK are not subject of this report.

2 Course of discussions

At the 201st meeting on 09/07/2009 /1/, GRS gave a report on GRS Information Notice WLN 2009/01 "Reactor scram due to temporary loss of the station service supply caused by a short-circuit in a generator transformer in the Krümmel nuclear power plant" on 28/06/2007 /2, 3/. In addition, the Committee was briefly informed about the events at KKK on 01/07/2009 (disconnection of a station service transformer by response of a protective device (Buchholz relay)) and on 04/07/2009 (failure of the generator transformer AT02 in July 2009 with turbine trip and reactor scram actuation).

At the 202nd meeting on 27/08/2009 /4/, TÜV Nord reported about inspection methods and ageing mechanisms of transformers and about the inspection programme for transformers that was developed by order of the MSGF /5 – 8/. Furthermore, the Committee was informed about the reportable event ME 2009/001 (Protective disconnection of an emergency power transformer by Buchholz relay response 10s following Buchholz alert in March 2009) /9/.

At the 203rd meeting on 12/11/2009 /10/, Prof. Gockenbach, Leibniz University Hanover, Head of the Schering Institute, Department of High Voltage Technology (IEH), reported in continuation of the 202nd meeting about ageing and monitoring measures relating to transformers /11/. Following that, representatives of the VGB working group "Transformer monitoring" presented a paper on the VGB monitoring concept for oil-paper-insulated transformers in German nuclear power plants /12/.

At the 204th meeting on 10/12/2009 /13/, GRS reported about the results of the examinations of the defective transformer AT02 from the Krümmel nuclear power plant at the Siemens transformer factory in Nuremberg, which took place end October/mid-November 2009 /14, 15/.

At the 206th meeting on 27/05/2010 /16/, the Committee members discussed in detail various aspects regarding the inspection concepts and identified the so-far unspecified need for further consultations.

At the 208th meeting on 22/10/2010 /17/, the Committee concluded the fact-finding process by hearing representatives of the VGB working group "Transformer monitoring" on the topic of the monitoring concept for dry emergency power transformers (cast-resin-insulated transformers) in German nuclear power plants /18/ and the handling of oil analyses /19/.

At the 209th meeting on 08/12/2010, the Committee members began discussing the draft report. At the 215th meeting on 13/12/2011, the Committee passed the text in hand.

3 Transformer types and structure of a transformer

There are oil-paper-insulated and dry transformers in use in the nuclear power plants. The insulation of an oil-paper-insulated transformer is based on wrapping of the copper conductor in paper and the oil filling of the vessel. Dry transformers have a solid-matter insulation, mostly of cast resin.

Apart from the kind of insulation of a transformer, the acting loads are also relevant for possible ageing processes. Therefore the transformers are classified in different performance classes. The performance spectrum of the transformers in a nuclear power plant ranges from 0.1 MVA to approx. 1100 MVA. The damaged KKK generator transformer, for example, had a rating of 740 MVA. The transformers stressed most during power operation are the generator transformers and the station service transformers. The offsite system transformers are not in use during normal operation but usually have a similar rating as the station service transformers. Less powerful transformers are the transformers of the unit generator and emergency generator systems (0.5 MVA to 4.2 MVA). The powerful transformers are all oil-paper-insulated transformers, the less powerful ones are oil-paper-insulated or dry transformers.

A power transformer essentially consists of the vessel, the electrical bushings, the iron core, the copper windings, the winding insulation, the insulating oil or a solid- matter insulation, and – as the case may be - the tap changers and the cooling system. In the case of the oil-paper-insulated transformers, the oil serves for cooling and for electrical insulation.

Cast-resin-insulated transformers, whose windings are cast in casting resin, and oil-paper-insulated transformers are in use as emergency power transformers.

4 Defect and failure statistics

Concerning the age structure of the transformers used in Germany, it was established that there are transformers in service that have a service life of more than 70 years. Many transformers were installed in the late 70s, so that there is an accumulation of transformers (220 kV and 400 kV) with a service life of more than 30 years. This is also the case worldwide. Available statistics /10, 11/ only contain information about the manufacturing age of the transformers and not about their loading periods. A generator transformer of a power plant in the base load range is close to full-load operation for approx. 8,000 hours per year. For comparison, a substation transformer of a 220 kV/400 kV substation is also online for approx. 8,000 hours per year, but at lesser load. Generally, there are few statistics available about transformer failure rates. For example, an international survey by CIGRE (International Council on Large Electric Systems) of 1983 lists annual failure rates of generator and substation transformers in dependence of different voltage levels. Generally, it can be said that the generator transformers have higher failure rates than the substation transformers. This can be put down to the higher loading of the generator transformers. The failure causes listed in the statistics concern mainly the windings (according to the CIGRE statistics approx. 43 %) and the bushings (according to the CIGRE statistics approx. 19 %) and hence the oil-paper insulation. Defects in the insulation are mainly due to deformation of the windings due to mechanical deformation caused by short-circuits, a relaxation of the restraining forces of the insulation material, or impurities. Ageing is only to a lesser extend considered to be the cause of defects, but the two last-mentioned mechanisms may also be caused by ageing.

The grid operators have monitoring programmes in place. Some of the grid operators maintain databases that contain inspection intervals for transformers sorted by loading, rating and relevance. The grid operators perform load flow calculations and record the voltage ratios, which can be recalled at any time. It is not possible on this basis to carry out assessments of peak loads or excess voltages that have occurred temporarily. Offsite lightning strike events in high-voltage power lines are listed. In general, full offsite load is assumed. The "Forschungsgemeinschaft für elektrische Anlagen und Stromwirtschaft e. V. (a research association for electrical installations and the electrical power industry) in Mannheim has been commissioned by the power utilities to keep damage statistics for the power grids, including i.a. statistics on transformers of different rating classes. According to those statistics, a transformer fire as it occurred at KKK is a rare event.

5 Oil-paper-insulated transformers

Degradation and ageing mechanisms of oil-paper-insulated transformers

For the development of the inspection programmes, the question was considered of which of the existing components of a transformer may lead to damage caused by ageing and what failure mechanisms have to be taken into account.

In the case of oil-paper-insulated transformers, the ageing-relevant components to be considered are mainly the electrical bushings, the windings, the insulation liquids and in part the tap changers. The vessel and iron core are less relevant. Hence the inspections of the insulating liquid are of particular relevance in the case of oil-paper-insulated transformers.

The ageing mechanisms of the individual components of a transformer are:

for the vessel and cooling system	corrosion, ageing of seals and dirtying.
for the winding insulation and the solid-matter insulation for support (paper, laminated paper and wood)	the depolymerisation of the paper, (independent of temperature and humidity) and mechanical loads (magnetically induced forces).
for the condenser bushings	depolymerisation as main ageing effect.

When partial discharges occur, the ageing of the insulation of windings and condenser bushings is accelerated.

Iron core and copper windings show no significant ageing processes. Damage on these components can be put down to manufacturing flaws and, in the case of the winding, also to short-circuit-induced loads. As regards the insulating oil, the phenomena concern thermal decomposition, oxidation through air, and dirtying.

The electrical and thermal loads are the dominating ageing effects compared with the mechanical and chemical effects. Electrical loading often leads to reactions with CO and CO_2 in the solid-matter insulation as well as sometimes to products in the oil such as furfural[1] (2FAL) and solid particles. These mechanisms eventually finally lead to the destruction of the paper molecule chains, i.e. to a decrease of the polymerisation value (DP: degree of polymerisation). The degree of polymerisation describes the length of the chains of sugar molecules of which the paper is composed and is thus a measure of the elasticity of the paper. The destruction of the paper molecule chains leads to the reduction of the paper's stability and hence also of the insulating effect and is irreversible. It is merely possible to delay the progression of the destruction.

The first indicator of a thermal loading of the oil is a release of hydrogen. Furthermore, a formation of different combinations of hydrocarbon[2] as well as additionally of CO, CO_2, acids and resins can be observed. As a result, the breakdown voltage of the oil is reduced. On the whole, however, contrary to the paper, it is possible to change the oil.

These ageing mechanisms can be accelerated by certain effects. The loading of the insulation leads to the ageing of the cellulose and the insulating oil and hence to an increase of the water content, with the increase in the water content leading in turn to an acceleration of ageing. The depolymerisation of the cellulose is irreversible. The formation of acids and impurities in the oil can be remedied by filtering or changing of the

[1] Furfural: 2-furaldehyde (2FAL), $C_5H_4O_2$, colourless liquid, changing to a slight brown colour, with a pungent sweet smell of bitter almonds, harmful, not readily soluble in water but easily soluble in oils and greases

[2] CH_4, C_2H_4, C_2H_6, C_2H_4,C_2H_2

oil. The formation of gas and sludge in the oil is also easily detectible. Locally increased thermal and electrical loads or their combination accelerate the ageing process. Experience shows that one can assume an accelerated ageing process to set in at a temperature of 100 °C. Due to the exponential relation (Arrhenius equation), doubling of the ageing velocity can be observed at every increase of 6 to 8 °C.

The depolymerisation of the cellulose caused by ageing leads to the break-up of the glucose ring chains and to the formation of water, gases (CO, CO_2), aldehyde groups[3] (alkaline, 2FAL) and carboxyl groups[4] (organic acids). As shown in measurements, the influence of the temperature on the depolymerisation velocity and the water content of the paper is very high. Moreover, the organic acids generated from ageing of the cellulose accelerate the ageing of the paper insulation. Here, metals such as copper, iron, aluminium and zinc have an increasing catalytic effect.

As regards electromagnetic impacts, strong currents, especially short-circuits, have high forces. These can lead to deformations of the winding, the ripping-open of the paper insulation, in particular in aged locations, and partial discharges up to breakdowns. Partial discharges at weak points may also occur as a consequence of excess voltages, caused e.g. by lightning strike or increased operational voltages in the event of a load rejection to auxiliary station supply. If the dielectric strength of a transformer that has aged in operation is reduced and the partial discharges do not stop by themselves with reducing voltage, such phenomena, too, can lead to a progression of the damage.

Thermal ageing is caused by the ohmic and magnetic losses occurring with the operation of the transformer. Electrical and dielectric ageing occurs due to the changes in the insulating materials as a result of their loading in the electrical field. Mechanical oscillations and vibrations (e.g. the typical "transformer humming" caused by the hysteresis of the iron), deposits on pumps and ventilators as well as the ageing of seals lead to the mechanical ageing of the transformer. Oxygen from the atmosphere together with the catalysts, such as copper and iron, present in the transformer lead to the formation of acid oxidation products, which in combination with water can in turn influence the dielectric and other properties of the oil. This latter effect is chemical ageing.

Critical ageing parameters, i.e. parameters that contribute considerably to accelerated ageing (of the insulation materials) are humidity, temperature and electric field strength. Humidity leads indirectly to the reduction of the electric strength and the mechanical strength of the paper insulation since the humidity leads to an accelerated depolymerisation of the paper. An increase of the temperature leads to the reduction of the mechanical strength of the paper insulation. A locally increased electric field strength, e.g. due to a location of defect in the insulation, may lead to partial discharges. Regarding humidity, care has to be taken in particular that the water content of the solid insulation material in the transformer is considerably higher than that of the liquid insulation at the same temperature. For example, if at an oil temperature of 60°C the water content in the oil is 40 ppm, the water content in the paper insulation is approx. 4 per cent by weight. In a transformer with 100,000 kg oil and 13,000 kg solid insulation, 4 kg water are bound in the oil and 520 kg water in the insulation under these boundary conditions. In equilibrium state, water diffuses from the oil into

[3] R-COH
[4] R-COOH

the paper at decreasing temperatures, and the process is reversed if temperatures rise. With 40 ppm to 50 ppm water content at 20 °C, normal mineral oil has reached saturation. The interaction described above has to be taken into account in the determination of the water content in the oil.

An equilibrium of the humidity distribution between oil and paper insulation in the transformers establishes itself at equal load following a certain operating time. For power transformers with varying loads, it is more difficult to reach a state of equilibrium.

With increasing humidity, the breakdown field strength decreases. At 50 % relative humidity already, a breakdown field strength of only about 50% is reached. Therefore the measurement of the breakdown field strength is mainly used according to DIN VDE to verify the amount of water (and particles) in the oil. Measurements of the loss factor tan δ, e.g. of an oil-paper bushing, also show the influence of the paper humidity as a function of the temperature.

The influence of load changes on the ageing of oil-paper-insulated transformers is low due to the good insulation.

Test and measuring methods for oil-paper-insulated transformers

Inspections of the insulating liquid are of particular relevance in the case of oil-paper-insulated transformers. In a dissolved-gas analysis (DGA), the development of corrosive gas in the oil is monitored. Thermal overloading or partial discharges lead to increased concentrations of certain gases or to defect-typical conditions of gas concentrations in the oil. The release of different gases depends on the temperature. Hence a distinction is made between the three temperature ranges of < 300 °C / 300 °C to 700 °C / > 700 °C which lead to the release of different gases. As regards the electrical discharges, a distinction is made between localised partial discharges, low-energy sparks, and high-energy electric arcs. The evaluation of the concentration and the conditions of the corrosive gases therefore allows a monitoring of trends to detect possible defects. The DGA is an instrument for the long-term condition monitoring of the transformer; it is not suited for quick damage ascertainment. The DGA can be carried out by way of manual sampling or by using a quasi-continuously-measuring online system. Results obtained from discontinuous manual sampling with subsequent analysis in an accredited test laboratory have to be seen as more comprehensive, more reliable and better reproducible than those of the online system.

An online system carries out the sampling at previously specified and programmable intervals. The monitoring of the trend of the analysis results over a longer period of time then provides a quasi-continuous distribution of the measured gas concentrations. If there are any significant changes in the gas concentrations measured by an online system, manual oil samples are taken and subsequently analysed comprehensively in an accredited test laboratory. On the basis of the results of this analysis it is then possible to define further necessary actions, if any.

According to the operators, a double determination is carried out if manual samples with subsequent DGA show significant deviations, i.e. the result of the measurement is checked for plausibility by two separate analyses. In the existing standards for the evaluation of the oil samples, the experience has been included that has been gained with the monitoring of a large number of transformers. This has yielded the mentioned concentration values for individual key gases in correlation with certain damage phenomena, but with the corresponding interpretation ranges. It is these concentration values that the power utilities as a reference. Any further insights that are gained are also taken into account. Experience shows that effects due to thermal faults have a slow lead time compared to electrical faults. In the assessment of the condition it is necessary to have an integrated view, i.e. the different test methods and results have to be considered as a whole. An important role is also played by the structure, the materials used, the components installed, and the loading condition of the respective transformer. It is necessary for the diagnosis to look at a complex picture.

According to the operators' information, regular DGAs are carried out on generator, station service and offsite system transformers. Should any changes in the readings occur that would point at any relevant damage, the transformers would be exchanged as a precautionary measure. It is not possible to use these readings for an assessment of the residual lifetime of a transformer. The experts have confirmed that these readings provide qualitative information about the condition of the transformers that can only be seen as being quantitative over a long period of time. Spontaneous failures due to local locations of defect cannot be excluded.

In oil tests according to DIN standards for the assessment of the electrical and tribological properties of the oil, the water content, viscosity, inhibitor content, colour, impurity etc. are examined. The determination of the water content allows a statement on the insulating properties. A high water content of the oil favours the decomposition of the paper and hence reduces the quality of the insulation. The entry of humidity in the vessel cannot be lastingly prevented. Also, the paper always has a residual humidity which over time will lead to the decomposition of the paper.

From the determination of the DP value with the help of manual paper sampling it is possible to make statements on the ageing condition of the insulation paper of oil-insulated transformers. It has to be taken into account, however, that such sampling is only possibly in a manner that is destructive, i.e. it cannot be performed onsite were the transformer is actually operational.

The number of sugar molecules (chain length) of which the paper is composed and the viscosity of the insulation paper that is dissolved in a special liquid correlate, so that it is possible to read the ageing condition of the paper from the chain length. New paper has a chain length of about 1,100 to 1,300 (=DP value) sugar molecules, which decreases with age or under thermal loading. A DP value of approx. 300 has to be regarded as critical. The validity of the determination of the DP profile, in which as many individual samples as possible are included, depends on the number of the samples and the consideration of the axial and radial distribution of the sampling locations in a winding.

A furan analysis of an oil sample taken from the transformer can allow a conclusion of the DP value, i.e. the number of glucose chains of the paper. In the case of new paper insulation with DP values of approx. 1200, there is no furan. If the DP value decreases to a level that indicates the limit of the mechanical resilience of the paper, the furan proportion rises exponentially. Hence the furan proportion of the oil is a good indicator of the lifetime of the paper. However, this measurement yields an integral result, so that small local locations of defect that may lead to a failure can only be detected with limitations. When assessing the results of furan analyses, this has to be taken into account accordingly. Results from the sampling of insulating paper from an aged transformer have yielded a standard deviation of the individual samples of approx. 240. This shows that a transformer for which a degree of polymerisation of approx. 550 has been determined from a furan analysis may well also show locations of the winding isolation that are already within a scope that has to be regarded as critical.

For the assessment especially of the mechanical condition of a winding, the measurements of the transmission ratios, the isolation resistances, the winding resistances, the short-circuit impedances and short-circuit losses as well as the capacity and tan δ measurements are used. A new diagnostic procedure is the frequency response analysis (FRA), in which the transmission behaviour of the transformer in a larger frequency range is determined. This method is suitable for detecting mechanical changes in the core and the windings. It is therefore recommended to carry out these measurements following a transport of the container and after the occurrence of faults involving high currents. The method is not suited as in-service inspection method. It is generally necessary for these measurements to perform comparative calculations (recourse to a reference measurement on a transformer that is demonstrably intact, "fingerprint") in order to detect changes. It is therefore recommended to carry out an initial measurement upon the installation of a transformer so that a comparison is possible if need be.

To assess the condition of the iron core, no-load-current/no-load-loss measurements are performed.

The influence of dynamic loads on oil-paper-insulated transformers is low except for short-circuits. At a certain degree of damage of the paper, the transformer is destroyed. It can only be established in a destructive tests whether the limit of mechanical resilience of the paper has been reached. It is not possible to determine fatigue mechanisms due to the complex structure of transformers. It is therefore expedient to continue developing methods for analysing the strength of the paper.

Winding deformations indicate overloading as a result of a short-circuit. So far it is not possible to quantify what progression of winding deformations has to be expected and whether this depends on the age of the transformer. There are studies going on into whether certain frequency analyses may allow any corresponding conclusions. How such conclusions might be evaluated is, however, still a subject of research. The influence of a short-circuit on the mechanical and electrical properties of a transformer is difficult to assess – except in the case of a total failure – as this can currently only be determined by means of destructive testing. The operators believe that an assessment is possible by combining e.g. frequency analyses and capacity measurements. According to this method it is possible within a certain bandwidth of the results to derive conclusions regarding the reliability performance of the transformer.

In all, most of the tests provide mainly integral results. Local damage is not immediately detectable. Due to the integral measuring methods, the detection of local damage is only possible after a certain time has elapsed. Local damage that causes e.g. an alteration of the hydrogen content can only be detected after a certain period of time, which may be several days. The result, however, would merely show that there is an ageing effect, which need not necessarily lead to a direct failure. The process usually is a steady one.

The DGA provides integral values. However, it may also point at local locations of defect as e.g. the increase of the hydrogen concentration may also indicate partial discharges. Measurements of partial discharges (PD measurements) serve for the identification of locations of defect in the insulation. With these measurements it is possible to establish directly whether partial discharges are occurring. With the help of e.g. acoustic measurements it is then possible to detect the local locations of defect in the insulation. In former times it was only possible to carry out PD measurements at the factory, in the meantime this has also become possible on site. Permanent online measuring would be possible, but is not appropriate due to the too large amount of data generated.

PD measurement is a discrete measuring method for the determination of local areas with increased field strength. These areas may have originated due to various causes, e.g. detachments within the solid-matter insulation or brought on by humidity in the solid-matter insulation, locations of defect in glueings, air pockets, free metallic particles, lacking contacting of shieldings, sharp metallic edges, or creepage currents. Local partial discharges cause i.a. heat, light, currents in external electric circuits, chemical processes, mechanical waves and electromagnetic radiation. These phenomena can be more or less well recorded by different measuring methods (electrical measuring, oil analysis, UHF probe, sensors). The methods producing results with the highest informational value are at present electrical measuring and oil analysis, and in special tests acoustic measurements. According to the experts, a three-year pilot project on PD measurements is currently on-going.

To develop measuring methods for partial discharges further, the IEH has installed a capacitance sensor for capacitative signal decoupling externally on the outside of a bushing. The signal is amplified and visualised via a fibre-optic cable with an oscilloscope. This measurement can be carried out at a bushing and at the neutral point. High-frequency measuring methods are mostly performed in combination with acoustic measures.

The bushings can be inspected for any changes from outside by capacity or tan δ measurements. In the case of large-scale degradation, damage on windings will also be visible after opening of the transformer through colouring of the insulation materials or through mechanical changes. With such damage, however, a root cause analysis is no longer possible in most cases.

To assess the condition and quality of the insulation, dielectric tests to determine the humidity of the paper and voltage tests with induced current are also performed. Paper samples can only be taken at the manufacturer's (see above remarks on DP determination).

For an assessment of the mechanical and electrical operational safety of the tap changers of generator transformers, electrical tests are carried out, like e.g. measurements of the contact resistance and pressure, function testing of the tap changers, and testing of the current draw of the tap changer drives. Regarding the ageing of tap changers, it was explained that this occurs much slower in the transformers of plants that are operated in the base-load range than in substation transformers, which show a considerably more intense dynamic behaviour.

Oil sample analyses that are carried out at regular intervals or specially for certain events serve for the determination of the oil parameters, the DGA, and the furan analysis. Nowadays, DGAs can also be carried out online at short intervals (within a range of hours as a minimum).

The interpretation of the DGA is based on empirical values. For example, changes in the measured values point at certain phenomena, which can be underpinned by taking other measured values into account. With the help e.g. of fuzzy logics across the combination of various measurements it is possible to make more accurate statements. This is a proven measuring method and has to this date been refined by improved recording systems. Combinations of different measuring methods and results provide the data base for trend monitoring. For example, one can use the "Duval Triangle" to assess whether there are any partial discharges or thermal faults.

One can derive different diagnoses from tan δ and capacity measurements of bushings. For example, a rise in capacity compared with reference measurements allows the conclusion that there are partial breakdowns, and high tan δ values indicate humidity, ageing, and partial breakdowns. Due to the geometrical configuration of the bushings, simple calculation models can be made. The above-mentioned measurements can also be carried out online. Bushings are also inspected with the help of thermography; this may allow the detection of local hot spots resulting from partial breakdowns.

Due to the lacking data base it is at present not possible to make any statements on how certain degradations of a transformer shorten its lifetime by a certain period. Transformer failures do not occur very often. Those transformers that can be examined after a defect mostly do not have a corresponding database of relevant measurements that would allow a statement on the incipient damage mechanism. With the measuring methods applied so far it is possible to make statements on the condition of the oil or the paper. Ageing phenomena can be detected with these methods, but it is not possible to make any statements on whether these phenomena are eventually fault-relevant. In most cases, the respective enterprises draw the corresponding consequences if ageing effects or failure mechanisms become apparent, and the oil or, if necessary, the transformer is exchanged. Hence any damage that has occurred is mostly not directly correlatable with the measuring results of the analyses.

To ensure the operational readiness of oil transformers, there are a range of operation monitoring systems available. These should also be examined with regard to their correct functioning. Monitoring systems can be verified e.g. by comparing the measured values with laboratory findings obtained from manually taken samples. Otherwise, the operational readiness of these installations is assured by the performance of optical inspections, oil level verifications, protection and monitoring installations of external system components, and cleaning.

Online measuring methods

DGAs can also be carried out online. When using a DGA online monitoring system, a transgression of predefined levels of attention could be detected and precautionary measures be taken immediately. A monitoring system cannot replace a protective installation /11/.

TÜV Nord and IEH recommend a daily DGA oil analysis for power transformers if an online monitoring system is used.

From the operators' point of view it is possible to use the content of hydrogen as key gas as an indication of a degradation of the transformer. Prior to any possible degradation of the transformer, one can initially observe a rise in the hydrogen content. Only then are further-reaching analyses of other gas concentrations or the presence of other gases of importance. Hence it is sufficient to monitor the hydrogen content continuously. Practical experience shows that the evaluation of oil samples that have been drawn over a longer period of time and analysed in external laboratories have yielded clearly better-reproducible results than on-site measurements.

According to TÜV Nord, not only continuous hydrogen concentration measurements but also the analysis of further key gases is recommendable. With the DGA, long-term monitoring is to be performed, allowing the monitoring of trends. This is to include the additional monitoring of the development of all key gases, not only of hydrogen. Moreover, the sensors measuring the hydrogen concentration are influenced in particular by CO and CO_2. With parallel measurements of the CO and CO_2 concentrations it is therefore possible to determine the hydrogen concentration more exactly, which allows more specific conclusions. Also, the drawback of the less-clearly reproducible results of the online measurements is compensated by the continuity of the measurements. In cases of doubt, an additional laboratory examination is considered advisable.

According to TÜV Nord, first experience has shown at what intervals discontinuous online measuring is useful. After an exchange of a transformer or an oil change, the measuring results will only become stable after a period of several months. It is therefore initially advisable to carry out frequent measurements to gain experience. After this phase, the measuring intervals may be extended as required and defined plant-specifically.

According to information provided by the IEH, experiments are currently going on in which the results of the monitoring systems are compared with those obtained from laboratory tests. This also includes an examination of in which locations and at what times during operation samples should be taken to obtain meaningful results. The findings from the experiments so far show that the online measurements reliably deliver results that are comparable to the laboratory measurements. However, there is not yet sufficient operating experience with this equipment available. Furthermore, the expected lifetime of these systems is much shorter than that of the transformers.

According to the operators, there is a great deal of experience with the laboratory analyses of the oil samples for the DGA available. At regular intervals, mostly once a year or during an overall maintenance inspection outage, oil samples are taken from the generator and power transformers and analysed in certified laboratories. At a switch to online monitoring systems it has to be ensured that these systems will reliably guarantee correct measurements. This is not the case so far. Transducer failures, measuring errors due to temperature influences and other disturbances have been observed, so that the information provided by the monitoring systems has not always been clear. None of the monitoring systems available is currently suited for deriving automatic measures from their measurements, like e.g. the disconnection of a transformer.

Monitoring systems are generally used with the aim to obtain extended information about the condition of the transformers. Overall, it is possible with these systems to enlarge the data base by their simple operation and trace back any incipient degradation in the case of a total failure. According to the VGB Instruction Sheet /20/, it is recommended to have all generator, station service and standby grid transformers equipped with a DGA monitoring system that can detect at least the hydrogen concentration by the end of 2010.

However, the oil and DGA analyses carried out in the laboratory also represent only a part of the overall assessment of a transformer. If there is any indication of a change in the measured values, especially upon the transgression of a level of attention from the DGA, this will be verified as soon as possible by experts, with consideration of all previous measuring results and an assessment of the condition of the transformer.

The use of monitoring systems for the monitoring of emergency power transformers is not purposeful due to the low utilisation of these transformers and their correspondingly slow ageing. In addition, emergency power transformers have considerable design margins. For monitoring systems, there is so far now verification of e.g. their stability during earthquakes for use in the safety system /12/. Overall, there is a lack of operating experience for such systems since there is presently no monitoring of transformers of this performance class, so that there is a high risk of misinterpretation.

Regulations and limits

Regulations that concern the transformers are contained in KTA Safety Standard 3701 "General Requirements for the Electrical Power Supply in Nuclear Power Plants" and especially in Safety Standard 3705 "Switchgear Facilities, Transformers and Distribution Networks for the Electrical Power Supply of the Safety System in Nuclear Power Plants".

As regards oil analysis evaluations, which form an important part of the monitoring and inspection scope of oil-paper-insulated transformers, the assessment criteria are the DIN EN standards DIN EN 60599 " Mineral oil-impregnated electrical equipment in service" (corresponds to VDE 370, Part 7) and DIN EN 60422 "Mineral insulating oils in electrical equipment - Supervision and maintenance guidance" (corresponds to VDE 370, Part 2). Neither of the two standards contains any limit values. It is stated in DIN EN 60422 that it is virtually impossible to assess operational oils or define limit values for every single operational application.

In DIN EN 60599, "typical values" for gas concentrations of the DGA are contained, which serve for the information and as orientation for an assessment. In addition, various evaluation methods are presented. In principle, an interpretation requires the monitoring of trends. Any decisions on the further operation of transformers that are solely based on individual results of DGAs are not purposeful.

Operating experience so far has shown that certain influencing factors are important in a DGA to prevent a wrong interpretation of the analysis results. According to the operators, this is why samples are only taken by trained expert personnel. Instructions exist for correct (manual) sampling. These samples will exclusively be evaluated in specially certified laboratories. Variations are possible as a result of the different analysis methods used by the various laboratories, so that these are not directly comparable. However, the results from one and the same laboratory obtained with one and the same method will be comparable. If there are any abnormalities, it may be necessary to analyse another sample.

It is not possible to make any clear statement about the condition of a transformer solely on the basis of the results of an oil analysis. Consideration of the history of the analyses and the assessment of further findings (type and specification, further oil analyses during operation) is necessary. Assessments solely on the basis of attention thresholds in connection with the oil are therefore not purposeful in most cases. They may, however, give first clues as to any unusual changes. So far, there is not much experience with special events for the oil analysis of low-capacity transformers, such as emergency power transformers. This is why the operators analyse the results and define and verify attention thresholds within the framework of the cyclically performed oil analyses. Once sufficient operating experience has been accumulated, the attention thresholds are then to be adapted, and a gradient criterion is to be introduced, if need be.

For power transformers – of which there are a large number in operation - there exists a much more extensive data base. In the standards mentioned above, the experience gained with the monitoring of a large number of transformers is taken into account. The power utilities are guided by the correspondingly derived concentration values.

Generally, a model is lacking which would allow a conclusion from existing data as to under which boundary conditions a transformer will have a certain lifetime left. With the limited experience available so far, it is merely possible to derive trends.

Inspection concepts for oil-paper-insulated transformers

Generally, those presenting their papers stated that there is a general understanding of the ageing mechanisms of transformers and of their causes. On this basis, the inspections were specified.

The aim of monitoring measures is the early detection of faults to reduce the failure rate and downtimes. Here, it is to be checked to what extent modern inspection and monitoring methods, such as online DGA monitoring and partial-discharge measurements, offer advantages in the assessment of the condition of oil transformers compared with the existing inspection and monitoring concept.

Two concepts were presented to the committee: the inspection and maintenance concept of TÜV Nord in collaboration with the IEH [Fig. 1, page 26] and the inspection concept of VGB. In the inspection concept of the authorised experts, the dry transformers are included. VGB had initially prepared its concept only for oil-paper-insulated transformers [Fig. 2, page 27] and developed a separate one for cast-resin-insulated emergency power transformers [Fig. 3, page 27]. The implementation of the inspection scope defined in VGB for oil-paper-insulated transformers was begun in all German nuclear power plants on 01/12/2009. If necessary, the monitoring concept for oil-cooled transformers in nuclear power plants is updated within the framework of the exchange of experience among all German nuclear power plants.

Due to the different designs and acting loads, the inspection concepts differentiate between the transformer groups of generator transformers, station-service transformers and emergency power transformers and between the inspection types of factory test, acceptance test and function test or tests at fixed intervals and special tests.

Factory and acceptance tests are carried out during the manufacture of new components. These tests are repeated to a reasonable extent following an overhaul that has retroactive effects on the object of inspection, e.g. following the renewal of a winding at the transformer factory. It was stated with regard to the factory and acceptance tests that these still reflect the state of the art in science and technology. For example, after these tests were carried out at the Unterweser nuclear power plant in 2009, two new generator transformers were installed. These tests involve the high loading of the transformers (e.g. withstand voltage test, switching impulse voltage test, partial-discharge measurement), but the latter are designed to bear such loads. A deterioration of the condition due to this acceptance tests need not be assumed.

In-service inspections or inspections at fixed intervals are carried out regularly. The respective test cycles are predefined. If any abnormalities are found, corresponding action is taken.

Special tests have to be provided if the "inspections at fixed intervals" have yielded any indicators and after special events have occurred, e.g. if the actuation of transformer-relevant unit protection criteria has taken place due to thermal or electrical overloading. The respective tests have to be tuned to the corresponding situations. The special tests are mainly carried out due to the results of preceding inspections; data of e.g. oil analyses are available. When choosing the kind of inspection, the condition, type, age, operating mode (permanent load, changing loads) and the relevance of the transformer (safety, availability) are the determining factors. The assessments are made by corresponding experts, such as the company's internal specialist department, the manufacturer, and independent experts.

The scope of the in-service inspections regarded as necessary according to the state of the art in science and technology increases with the level of performance of the transformers. Hence, for the most powerful transformers in the station service system (generator transformers up to 1,100 MVA) there are the strictest requirements with regard to the use of monitoring systems (thermal and electrical loading). In the emergency power area, there are only smaller transformers (0.5 – 4.2 MVA) in use that are permanently loaded below the nominal rating as powerful safety-relevant consumers (drives) are not challenged during the normal operation of the plant. Compared with the generator and station service system transformers, these transformers are therefore subjected to lesser thermal loading (ageing).

The transformers correspond to a specification according to which they are designed for maximum operation, not for normal operation. Hence design margins exist. This design was based on a service life of approx. 30 years. Each postulated load that would reduce the lifetime of a transformer but that has not occurred therefore extends its service life. It also has to be considered that paper has a very long service life (> 100 years). It is only the interaction of temperature, humidity and electrical loads that puts the overall service life of a transformer to a certain degree into perspective. The manufacturers do not warrant for the entire service life of a transformer.

According to VGB, this inspection concept has meant a harmonisation of inspections in all German nuclear power plants. Inspection cycles have partly been shortened. Additional measurements, except for the use of the monitoring system, are not provided by the VGB inspection concept. Operational monitoring, like e.g. temperature measurements, are not specially listed in the inspection concept.

TÜV Nord and IEH regard the existing concept of inspections in the form of in-service inspections and special inspections as viable. For the most powerful transformers there are the strictest requirements with regard to the use of monitoring systems for thermal and electrical loading. Improvements of the monitoring are possible through online methods for DGA or DG registration besides the other parameters like current, voltage and temperature. Monitoring systems are no protection systems. They serve for the identification of trends and for early warning in the case of any degradation in the performance of the insulation system. Monitoring systems cannot prevent any spontaneously occurring defects. A general need for further research is seen. According to /11, slides 16-19/ it shows that overall, there are few transformers failing, given their large total number and the long service times.

According to the VGB, the VGB inspection concept has been in place in all German nuclear power plants since 01/12/2009. The conventional power plants were also recommended to apply this concept. The VGB stressed that the concept presented for power transformers, initiated by the event at KKK, was the result of a jointly prepared agreement within the VGB and was a voluntary measure. It comprises in particular a harmonisation of the inspections carried out so far. An information exchange with the authorities is intended.

Differences between the two inspection concepts

The differences between the two inspection concepts are slight. Instead of an annual inspection cycle, the VGB inspection concept proposes i.a. an inspection cycle that depends on refuelling, which in some plants is carried out after 15 months, for the inspection and maintenance of the tap changer as well as for the function tests of the protective equipment.

Both inspection concepts provide an annual laboratory test with full gas analysis for the DGA. According to the inspection concept of the experts, daily online measurements with full gas analysis are additionally recommended. In the VGB inspection concept, the monitoring systems employed for the generator transformers are not specially listed in the tables but are used nevertheless. However, the VGB concept does not provide any requirements for the monitoring systems as these are not reliable enough. According to the VGB Instruction Sheet /20/, it is recommended to have all generator, station service and standby grid transformers equipped with a DGA monitoring system that can detect at least the hydrogen concentration by the end of 2010.

6 Dry transformers

Degradation and ageing mechanisms of dry transformers

The inspection methods for the early detection of faults and for ensuring operational readiness of dry transformers differ in part from those for oil-insulated transformers. Dry transformers count among the low-capacity transformers; they are operated i.a. as emergency power transformers. All emergency power dry transformers used in German nuclear power plants are cast-resin-insulated transformers in which the high-voltage winding is fully cast in epoxy resin. The low-voltage windings are mostly implemented as strip winding (aluminium foil), which is also cast in a solid epoxy resin block. Hence, hardly any air, humidity and dust can reach the windings. Compared to pure air insulation, a higher resistance to partial discharges, short-circuits and voltage surges is thereby achieved. Above the low-voltage windings, a thermistor sensing element is installed to monitor the transformers for thermal overloading and cooling faults. Cast-resin-insulated transformers are largely maintenance-free.

Regarding possible ageing mechanisms, parts of the dry transformer that need to be considered are the insulating system, the iron core, the windings and, if present, the protective housing. The cast-resin system ages very slowly, so that no significant ageing processes are discernible in the insulation system. Only the molecular structure has to be monitored for any change due to thermal loading. In addition, impurities may occur. The iron core and the windings, too, do not show any significant ageing processes. If there is any damage of the corrosion protection, there may be corrosion on the iron core, which, however, is easily detectible. The outer protective housing may also corrode, but in most cases does not exist anyway.

In the case of the dry transformers, frequent load changes may lead to local delamination of the insulation.

The emergency power dry transformers are subject to little thermal loading during normal operation, so that the ageing processes are slowed down compared with the other transformers. Moreover, they are protected against environmental impacts as they are located inside closed service compartments.

Test and measuring methods for dry transformers

According to the manufacturers, cast-resin-insulated dry transformers are practically maintenance-free. In the opinion of the authorised experts, locations of defect in the insulation can be identified with the help of thermography. Moreover, the core bandages can be controlled and noise measurements and optical inspections can be carried out. Also, the functioning of protective and monitoring devices is verified.

There is no operating experience with regard to findings on dry transformers available for emergency power cast-resin-insulated transformers in German nuclear power plants. However, a low insulation resistance was detected during a special test on a recirculation pump transformer of a plant. This special test was performed because water had entered in connection with fire-fighting activities. Checks on the providently exchanged transformer showed that bandages of the core had become loose.

According to VGB, no damage on dry transformers caused by faulty auxiliary systems has been observed. The dry transformers have no ventilation systems of their own; they are cooled by room air. Depending on the ambient conditions of the transformer location, it may be that the transformer could heat up if the building ventilation was lost for a longer period of time. According to VGB, there is no known case of a failure of a dry transformer as a results of a loss of ventilation.

According to VGB, sufficient space has to be available for applying thermography to a transformer under voltage in order to be able to obtain measurements with informational value and carry them out without any risk to the personnel. For emergency power dry transformers, this is often not the case. Furthermore, it is easy to detect during the overall maintenance inspection outage any discolourations on disconnected transformers that are due to increased heat generation. This is why thermography is generally only applied as a special test method.

The IEH has carried out experiments regarding temperature monitoring for dry transformers. Here, a fibre optic cable was connected as sensor to different locations on a transformer and connected to the circuit breaker. At high temperatures, e.g. due to a short-circuit, the fibre optic cable melted and the circuit-breaker opened, thus disconnecting the transformer from the grid. In the experiment, two transformers were operated in parallel as redundancy. In the meantime, a total of transformers in parallel operation have been fitted with such sensors, and operating experience so far has been positive.

Inspection concepts for dry transformers

The inspection concept of the authorised experts also includes the dry transformers [Fig. 1, page 26]. In analogy to the oil-paper-insulated transformers, the VGB inspection concept for the emergency power cast-resin-insulated transformers [Fig. 3, page 27] provides for the division into three inspection types of factory tests, tests at fixed intervals, and special tests.

As according to the manufacturers the dry transformers are practically maintenance-free, one inspection in one redundancy section is carried per refuelling outage. Furthermore, optical inspections are carried out on each round. In the nuclear power plants, these rounds are done at different intervals, but in narrow cycles. Otherwise, special tests are carried out depending on the findings. The corresponding factory and acceptance tests take place during and after manufacturing.

In the opinion of VGB, the measures described for monitoring and assessing the condition of emergency power cast-resin-insulated transformers are suited for ensuring an apt operational condition. Moreover, the monitoring concept for emergency power cast-resin-insulated transformers in nuclear power plants is updated if need be within the framework of the exchange of experience across all German nuclear power plants. Monitoring of the same kind is ensured by the jointly specified inspections for transformers.

Differences between the two inspection concepts

The differences between the two inspection concepts are slight. In the case of the dry transformers, TÜV Nord and IEH suggest thermography as in-service inspection. According to VGB, thermography is generally only used as an inspection method for special tests.

7 Assessment by the Committee

The VGB inspection concept for oil-paper-insulated transformers has been implemented in all plants since 01/12/2009. The VGB Instruction Sheet /20/ defines a standardised inspection concept for all plants. The VGB inspection concept essentially takes the proposals of IEH and TÜV-Nord into account. The Committee assumes that the current inspection programmes have been implemented, considering the VGB test programme as the minimum standard.

As far as the Committee is aware, a large number of the transformers in use in German nuclear power plants have already been in service for a long time, especially in the medium-power range, so that further cases of transformer damage cannot be excluded.

With increasing age of the nuclear power plants and thus of the transformers, especially the generator transformers that are subjected to higher loads than e.g. the emergency power transformers, a relative accumulation of failures can be observed.

In the years 2007, 2009 and 2011, three generator transformer failures have occurred in North German plants.

The first failure in 2007 was in connection with an oil fire that damaged the transformer to such an extent that it was no longer possible to establish the cause of the failure.

The cause of the damage that occurred in 2009 was seen to be an interturn fault. Despite more detailed analyses it was not possible to clearly establish the underlying cause of the interturn fault. However, the authorised experts did not exclude a local degradation of the insulation in the transformer due to the service life and the loads that had acted on the transformer until that date. This was justified by referring to the results of the evaluation of the paper samples from the winding insulation of the destroyed transformer. The average value of the DP values (510 for the conductor insulation) had shown the paper insulation to be in still quite a good condition. Taking the standard deviation into account, it was considered to be possible, however, that local areas showed a DP value near or below the value of 150 to 200, which is regarded as critical. The results of the furan analysis carried out before, which can, however, only provide integral information on the condition of the winding insulation, had to that date not given any cause for questioning serviceability. As regards the validity of the evaluation of paper samples and furan analyses, reference is made to the remarks made in the section on "Test and measuring methods for oil-paper-insulated transformers" in this report. Hence the failure of this transformer may well have had its cause in an ageing-related local degradation of the paper insulation; however, a short-circuit in the previous year and the resulting loads could not be excluded either as having caused the failure.

The online DGA monitoring system that had been installed on the transformers shortly before had not shown any abnormalities, e.g. in the form of changing trends in the concentrations of the monitored key gases, in the days before the failure; it had, however, only been in service for scarcely two weeks when the failure happened.

The failure of the generator transformer in 2011 occurred spontaneously, like the two damage cases mentioned above. The transformer tests that had been agreed following the introduction of a test programme for condition monitoring had been carried out on the affected transformer in 2008 as part of a special test.

The online DGA monitoring system that had been installed on this transformer had previously not indicated any extraordinary changes in the gas concentration of the monitored key gases. Even after the reprocessing of the oil in 2007, the gas quotient for CO_2/CO for this transformer was above 10 (before, the average had been approx. 15mn with individual measurements of up to 25) and thus provided an indication of advanced ageing of the paper insulation. However, the furan measurements that were subsequently performed did not confirm this result. To this day (December 2011), the cause of this failure has not been established as the transformer has not yet been dismantled and the evaluation of the recently taken paper samples has not yet been concluded.

In another plant, a generator transformer was exchanged in 2008 as a precaution after a deviation in the winding resistance of a phase from the value established in the factory tests was found during a previous inspection. It was established that a solder joint in a strand was not conform with the manufacturer's specifications.

Even though there were indications of ageing being the cause of the failures in the cases mentioned above, it can be gathered overall from the presentations that it is not possible to derive an end of the service life from the measurements that have so far been carried out on the transformers. The failures that have become known concerned both transformers with a service life so far of 25 to 30 years and newly installed transformers. A verified database of measuring results from which specific ageing phenomena and failure rates could be derived does not exist. As a result of the failures in KKK, harmonised inspection programmes were initiated. According to current knowledge, no defined operating lifetime can be recommended for a preventive exchange.

The Committee recommends that the degradation mechanisms of the transformers that have failed should be investigated and compared with the data that have been obtained by various measurements.

According to the authorised experts, there are no models available that might be used for concluding from the existing data under which boundary conditions a transformer will have a certain residual lifetime. With the operating experience available so far, it in only possible to derive a trend. It was generally confirmed that spontaneous failures are not foreseeable. However, it is assumed that with the implementation of the inspections according to the inspection programmes, it will be possible to estimate the consequences of ageing effects and loads much better. The VGB programme /20/ comprises i.a. a minimum scope of in-service inspections to be carried out within indicated time intervals on generator, station service, offsite system and emergency power transformers. In future, the VGB is to update whenever necessary the monitoring concept for transformers in nuclear power plants within the framework of the exchange of experience across all German nuclear power plants. It has to be expected that with increasing operating experience, the inspections will provide more meaningful results.

Regarding the DGA monitoring systems, the Committee comes to the conclusion that there is as yet only little operating experience available. According to the authorised experts, the systems currently available are not sufficiently reliable (high failure rates, unreliable measuring results). According to the VGB Instruction Sheet, it is recommended to have all generator, station service and standby grid transformers equipped by the end of 2010 with a DGA monitoring system that can detect at least the hydrogen concentration. The authorised experts recommend to cover all key gases in order to be able to assess the results according to DIN EN 60599 if need be. If the measurements indicate any degradation, the results should first be verified by the taking of oil samples and carrying out laboratory measurements; only then should further measures be taken. So far, the DGA online monitoring systems do not show the necessary reliability that would be required for deriving direct measures. Any slowly developing degradation mechanisms can be detected by online DGA and manual laboratory analyses that are to be carried out at regular intervals according to both the VGB inspection programme and the IEH inspection programme. In the opinion of the VGB, any fast-progressing processes are always associated with a change in the hydrogen concentration, so that online hydrogen monitoring and, in the case of any findings, an analysis of all key gases in an accredited laboratory will be sufficient. At present is it not possible to derive any statements about the ageing condition of the transformer on the basis of these analyses alone. Only after the presence of the results of additional, verifying inspection steps (e.g. in the form of special tests) may it be possible to draw any conclusions with respect to the overall condition of the transformer.

In the opinion of the Committee, the experience yet to be gained with the DGA online monitoring systems should be awaited before any corresponding recommendations are made.

It has been reported by the authorised experts and the operators that the derivation of limit or reference values from the DGA analyses is very difficult. Experts recommend not to look at the absolute values alone but also at the history of measured values. In summary, the Committee considers it suitable to observe the time history of the gas concentration to derive further measures for determining the condition of a transformer if a trend is discernible. To this end, a DGA has to be performed regularly, i.e. at intervals that are adapted to the condition of the transformer and the diagnostic targets. In most cases, an interpretation on the basis of individual measuring results is not possible. In the opinion of the Committee, a determination of defined limit values for the DGA of transformers is not purposeful according to current knowledge. At present, there is no meaningful database. The Committee considers a collection of operating experience and the determination of attention thresholds by comparison of the results obtained from transformers with similar performance levels to be useful. In the opinion of the Committee, the main focus should be on the trend analyses. In all, the DGA represents only one measuring method, albeit an important one, of the entire inspection scope for oil-paper-insulated transformers.

According to authorised experts and operators, spontaneous transformer failures cannot be prevented. The causes of transformer failures can often not be determined anymore due to the damage done. Regarding these causes, manufacturing faults or load processes may be relevant. The Committee's view is that there is at present only little information available with regard to the load processes. For example, no studies exist of what effect harmonics in the grid have on the loading of the transformers. The Committee believes that these and other effects should in future be investigated.

In summary, the Committee considers the harmonisation of the inspection requirements for transformers in German nuclear power plants to be expedient and therefore welcomes the development brought about by VGB and TÜV Nord/IEH.

What significance is attributed to the inspection of the transformers depends on their safety significance. If transformers are installed within the safety system, corresponding requirements have to be fulfilled. The inspection requirements for transformers in operational installations serve i.a. for a high level of availability of the station service supply. Thus their implementation in the German nuclear power plants and the related requirements should be as standardised as possible.

The failure of transformers is covered by the safety concept of the facilities. Moreover, in terms of precaution on level of defence 1, maintenance has to be ensured that will keep failures, also of operational systems, that may lead to a load for the plant to a low state-of-the-art level. The monitoring programmes of VGB and TÜV Nord/IEH are largely the same and appear to be sufficient to the Committee to ensure monitoring of the transformers with the current knowledge available. The results of the programmes should be presented to the Committee in about a year's time.

Documents

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/8/ TÜV Nord SysTec, Dipl.-Ing. W. Reßing, „Prüfkriterien für Prüfungen der Isolierflüssigkeit“, Stand: 2009-08-08

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/13/ Ergebnisprotokoll der 204. Sitzung des Ausschusses ELEKTRISCHE EINRICHTUNGEN am 11.12.2009

/14/ Verstegen, Gesellschaft für Anlagensicherheit und Reaktortechnik (GRS), „Kurzbericht über die Untersuchung des Transformators AT02 des KKK im Siemens Transformatorenwerk Nürnberg“

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8 Annex

Figures 1 – 3 show the inspection and maintenance concepts of the authorised experts and of VGB

	Individual tests																				Maintenance			
	Oil inspections			Electrical measurements																	Inspections			
	Transformer														Bushings									
	DGA	Furan analysis (2 - Furfural)	Inspection of the insulating liquid (scope according to DIN EN 60422)	Transmission ratio	Insulation resistance	Short-circuit impedance	Winding resistors	Winding capacities	tan δ winding	Transmission behaviour (FRA)	No-load current	Humidity in the paper (PDC/FDS/RVM)	PD measurement	Voltage test with induced current	DGA	tan δ high-voltage bushing	Capacity high-voltage bushing	TE measurement high-voltage bushing	Oil humidity measurement	Thermography	Protection devices - function tests	Optical inspection	Tap changer	Tap changer inspection
Test cycles in years; x_s -special tests; [1] regular control [2] condition: instrument terminal provided; 1FE: once per refuelling, 4FE: one redundancy section per FE																								
Gen. tran.	1	3	1	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	4 [2]	4 [2]	x_s	x_s	x_s	1FE	[1]	1FE	8
Stat. serv. tran.	1	3	1	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s						x_s	1FE	[1]	1FE	8
Standby gr. tran.	1	3	1	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s		4 [2]	4 [2]	x_s		x_s	1FE	[1]	1FE	8
Emerg. pow. tran.	1	3	2	x_s	x_s	x_s	x_s	x_s	x_s		x_s			x_s						x_s	4FE	[1]	x_s	

Fig. 1: Maintenance concept and inspection scope according to IEH and TÜV Nord inspection programme for oil-paper-insulated and dry transformers /5/

	Individual tests																				Maintenance			
	Oil inspections			Electrical measurements																	Inspections			
				Transformer											Bushings									
	DGA	Furan analysis (2 - Furfural)	Inspection of the insulating liquid (scope according to DIN EN 60422)	Transmission ratio	Insulation resistance	Short-circuit impedance	Winding resistors	Winding capacities	tan δ winding	Transmission behaviour (FRA)	No-load current	Humidity in the paper (PDC/FDS/RVM)	PD measurement	Voltage test with induced current	DGA	tan δ high-voltage bushing	Capacity high-voltage bushing	TE measurement high-voltage bushing	Oil humidity measurement	Thermography	Protection devices - function tests	Optical inspection	Tap changer	Tap changer inspection
Test cycles in years; x_s -special tests; [1] regular control [2] condition: instrument terminal provided; 1FE: once per refuelling, 4FE: one redundancy section per FE																								
Gen. tran.	1	3	1	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	4 [2]	4 [2]	x_s	x_s	x_s	1FE	[1]	1FE	8
Stat. serv. tran.	1	3	1	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s						x_s	1FE	[1]	1FE	8
Standby gr. tran.	1	3	1	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s		4 [2]	4 [2]	x_s		x_s	1FE	[1]	1FE	8
Emerg. pow. tran.	1	3	2	x_s	x_s	x_s	x_s	x_s	x_s		x_s			x_s						x_s	4FE	[1]	x_s	

Fig. 2: Maintenance concept and inspection scope according to VGB inspection programme for oil-paper-insulated transformers /12/

	Transmission ratio	Insulation resistance	Short-circuit impedance	Winding resistors	Winding capacities	tan δ winding	Transmission behaviour (FRA)	No-load current	Thermography	PD measurement	Voltage test with induced current	Optical inspection	Protection devices - function tests	Inspection	Boresonic inspection
Test cycles xs: special tests; R: regular in-service control; 4FE: one redundancy section per FE															
Emergency power dry transformer	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	x_s	R	4FE	4FE	x_s

Fig. 3: Maintenance concept and inspection scope according to VGB inspection programme for dry transformers /18/